Continuous-wave, single-frequency, solid-state blue source for the 425–489 nm spectral range

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We report a new source of cw, single-frequency radiation in the blue, offering extended tunability and practical powers in a compact, all-solid-state design. The device is based on a green-pumped, cw, singly resonant optical parametric oscillator using MgO-doped stoichiometric lithium tantalate (MgO:sPPLT) as the nonlinear material. By internal second-harmonic generation of the resonant near-infrared signal radiation in a 5 mm BiB_3O_6 crystal, we generate nearly 450 mW of cw, single-frequency blue power over a tunable range of 425–489 nm with a linewidth of 8.5 MHz and a Gaussian spatial beam profile. The demonstrated wavelength coverage can be further extended by using alternative gratings for the MgO:sPPLT crystal.

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Continuous-wave solid-state blue sources are of practical interest for applications in optical data storage, laser displays, spectroscopy, medical diagnostics, and underwater communication. While cw diode lasers in the blue are available, output power, beam quality, and extended wavelength coverage still remain important limitations. Other well-established techniques, including second-harmonic generation (SHG) of near-infrared laser diodes [1] or the short-wavelength transitions in, for example, Nd:YAG [2] and $Nd:YVO_4$ [3], can provide practical cw powers in the blue, but similarly offer little or no tunability. Frequency doubling of the Ti:sapphire can in principle provide tunable coverage in the 400–500 nm range, but at increased cost and complexity, while similar approaches based on alternative diode-pumped vibronic gain media such as Cr:LiSAF have achieved limited power in the blue over a confined tuning range (427–443 nm) [4]. At the same time, all the described techniques suffer from the common drawback that the attainable spectral range in the blue is ultimately constrained by tunability of the fundamental input lasers, making the 400–500 nm range the current practical limit.

In this Letter, we describe a new approach to the generation of cw radiation in the blue, which offers the advantages of wide tuning range; practical output power; single-frequency performance; and simple, compact, solid-state design. The approach is based on intracavity SHG of a green-pumped, cw, singly resonant optical parametric oscillator (SRO) with MgO-doped stoichiometric lithium tantalate (MgO:sPPLT) as the nonlinear crystal [5,6]. We recently used this technique to produce femtosecond pulses in the ultraviolet [7]. Here, we extend this approach to the cw regime to generate up to 448 mW of cw, single-frequency blue radiation across 425–489 nm. Our approach also offers an important inherent advantage over alternative methods by permitting flexible wavelength coverage beyond the current limits through a suitable choice of grating period in the MgO:sPPLT crystal.

The configuration of the cw SRO (Fig. 1) is similar to that described in our earlier work [6]. The cavity is formed in a ring, comprising two concave reflectors, M_1 and M_2 ($r=50$ mm), and two plane mirrors, M_3 and M_4. Limited by physical constraints, the angle of incidence on M_1 and M_2 is kept $<7.5°$ to minimize astigmatism. The mirrors M_1, M_2, and M_3 are all highly reflecting ($R>99.9\%$) for the resonant signal (840–1000 nm). Mirror M_4 also has high reflectivity for the signal ($R>99\%$ over 850–920 nm, $R>99.9\%$ over 920–1000 nm), and high transmission ($T=85\%-90\%$) over 425–500 nm. All mirrors are also highly transmitting ($T=85\%-90\%$) for the idler (1100–1400 nm), thus ensuring SRO operation. The nonlinear crystal is MgO:sPPLT ($d_{\text{eff}}\sim 10$ pm/V). It is 30 mm long, contains a single grating ($\Lambda=7.97$ μm), and is housed in an oven with a temperature stability of ±0.1°C. The crystal faces have antireflection (AR) coating ($R<0.5\%$) for the signal (840–1000 nm), with high transmission ($T>98\%$) for the pump at 532 nm. The residual reflectivity of the coating is 0.6% to 4% per face for the idler

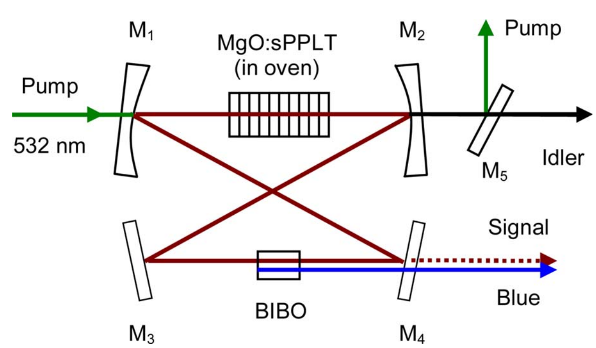

Fig. 1. (Color online) Schematic of the intracavity frequency-doubled MgO:sPPLT cw SRO for blue generation.

(1100–1400 nm). The pump source is a frequency-doubled, cw, single-frequency Nd:YVO_4 laser, as described previously [5,6].

For internal SHG we used BiB_3O_6 (BIBO) as the nonlinear crystal owing to its high nonlinear efficiency and low spatial walk-off [8,9]. The crystal is 5 mm in length and 4 mm × 8 mm in aperture. It is cut for type I phase matching ($ee \rightarrow o$) in the optical yz plane ($\varphi = 90°$) at an internal angle $\theta = 160°$ at normal incidence ($d_{\text{eff}} \sim 3.4$ pm/V), corresponding to a fundamental wavelength of ~920 nm. The crystal end faces are AR coated for the resonant signal ($R < 0.5\%$ over 850–1000 nm) and the SHG wavelengths ($R < 0.8\%$ over 425–500 nm). For the SRO, we use a relatively strong pump focusing parameter of $\xi_{\text{SRO}} = 2$, corresponding to a pump beam radius of $w_{op} = 24\ \mu$m inside the MgO:sPPLT crystal [5,6]. The signal beam waist is $w_{os} \sim 31\ \mu$m, resulting in optimum mode-matching to pump ($b_s = b_p$). The BIBO crystal is located at the second cavity focus between M_3 and M_4. The signal waist at the center of the crystal is ~160 μm, corresponding to a focusing parameter $\xi_{\text{SH}} \sim 0.015$. Such loose focusing was used to ensure an effective interaction length in BIBO, limited by spatial walk-off, equal to or longer than the crystal length. The total optical length of the cavity including both crystals is 298 mm, corresponding to a free-spectral range (FSR) of ~1.01 GHz. Unlike our previous work [6], the SRO cavity here does not include an intracavity etalon.

By varying the MgO:sPPLT crystal temperature from 71°C to 240°C, the signal could be continuously tuned from 978 to 850 nm (idler from 1167 to 1422 nm) [6]. The corresponding SHG wavelengths from 489 to 425 nm are generated by varying the internal angle of the BIBO crystal from 163.8° to 155.2°. We recorded the blue power near the maximum of the idler power for each crystal temperature by optimizing the input pump power before the onset of saturation [6]. Figure 2(a) shows the extracted blue power across the tuning range. The measured power varies from 45 mW at 425 nm to 300 mW at 489 nm, with as much 448 mW available at 459 nm.

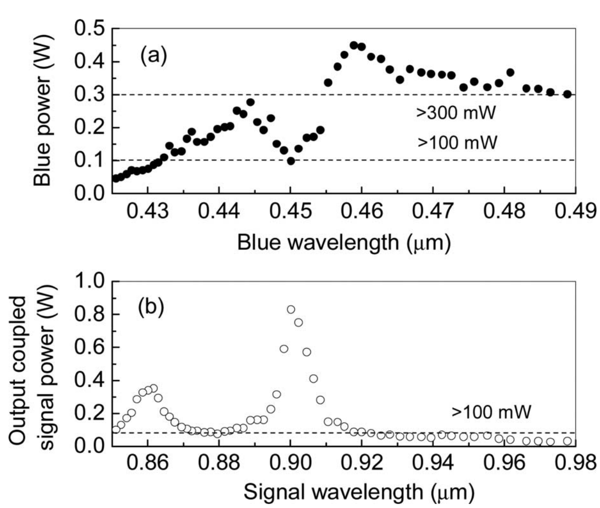

Fig. 2. (a) Second-harmonic blue power versus wavelength and (b) outcoupled signal power across the tuning range.

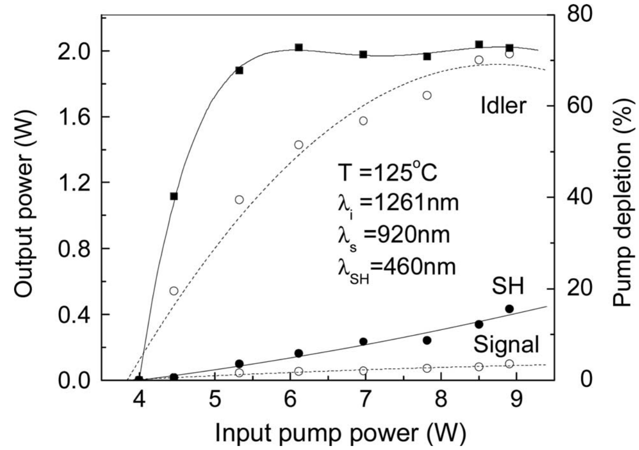

Fig. 3. Single-frequency blue power, signal power, idler power, and pump depletion as functions of input pump power to the frequency-doubled cw SRO. Solid and dotted curves are guides for the eye.

We extracted >300 mW of blue power over 53% of the tuning range and >100 mW over 90% of the tuning range. The sudden fall in the blue power near 450 nm is due to the rise in signal coupling loss through mirror M_4 [Fig. 2(b)], which results in reduced intracavity signal power and thus lower SHG conversion efficiency. As such, the use of a more optimized coating for M_4 with minimum transmission loss across the signal tuning range will readily overcome the dip in second-harmonic power. The overall decline in blue power towards the shorter wavelengths is, however, attributed to the reduction in intracavity signal power owing to the increased effects of thermal lensing near the extremes of the SRO tuning range (higher temperatures), higher MgO:sPPLT crystal coating losses, and parametric gain reduction away from degeneracy, as observed previously [6].

From the transmission data of the mirror M_4 and the outcoupled signal power [Fig. 2(b)], we calculate the intracavity signal power to vary from ~170 W at 978 nm to ~35 W at 850 nm, representing a maximum single-pass SHG efficiency of 0.29%. As evident in Fig. 2(b), there is also >100 mW of useful signal

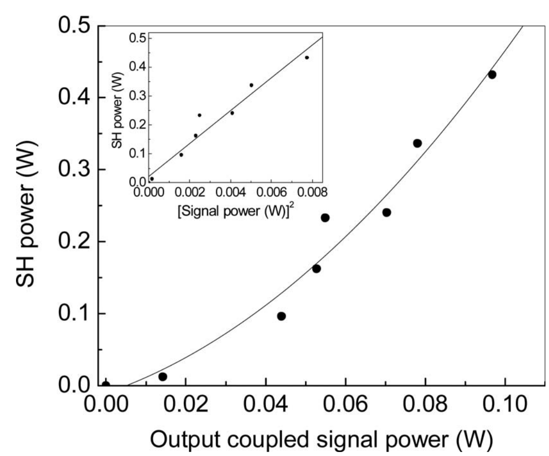

Fig. 4. Variation of SHG power with outcoupled signal power, showing a quadratic dependence. Inset, linear dependence of SHG power on the square of outcoupled signal power.

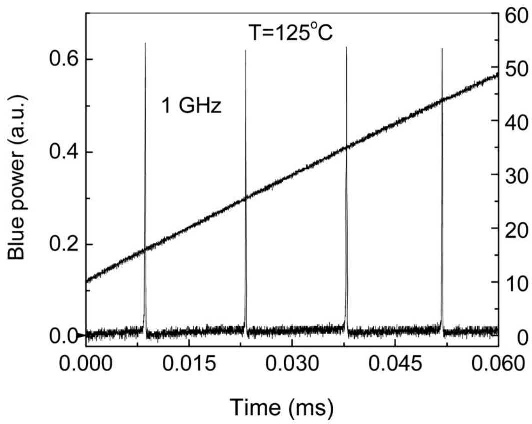

Fig. 5. Single-frequency spectrum of the generated blue light recorded by a scanning Fabry–Perot interferometer.

output available over 850–915 nm (50% of total signal tuning range), with 830 mW at 900 nm. In addition to the blue and signal, the SRO simultaneously generates substantial levels of nonresonant idler power of as much as 2.6 W across the 1167–1422 nm tuning range. The pump depletion exhibits a similar behavior to our earlier reports [6], varying from ~73% to ~48% throughout the tuning range.

We investigated the threshold and power scalability of the SRO near the maximum SHG power (at 460 nm), with the results shown in Fig. 3. At the maximum input pump power of 8.9 W, we obtained 432 mW of blue, 97 mW of outcoupled signal, and ~1.98 W of idler power, with a corresponding pump depletion of ~73%. The SHG power exhibits a nearly linear rise with the input pump power. The pump power threshold for the frequency-doubled SRO is 4 W (2.4 W without the BIBO crystal). The rise in threshold is due to the reflection loss of the BIBO crystal faces at the signal wavelength.

To gain further insight into the SHG process, we recorded the blue power as the function of the outcoupled signal power by varying the input pump power, with the results shown in Fig. 4. As expected, the increase in SHG power with outcoupled signal power is seen to be quadratic, also implying quadratic variation with the intracavity signal power. The inset of Fig. 4 also confirms the linear variation in SHG power with the square of the outcoupled signal power as expected.

We analyzed the spectrum of the generated blue light using a confocal scanning Fabry–Perot interferometer (FSR=1 GHz, finesse=400). A typical transmission fringe pattern at maximum blue power at 460 nm is shown in Fig. 5, confirming single-frequency operation with an instantaneous linewidth of ~8.5 MHz. Similar behavior was observed across the tuning range in the blue.

The recorded far-field energy distribution of the blue beam at 460 nm is also shown in Fig. 6. The oblique line pattern on the color beam plot in Fig. 6(a) is interference fringes caused by attenuation optics used to reduce blue intensity to the beam profiler.

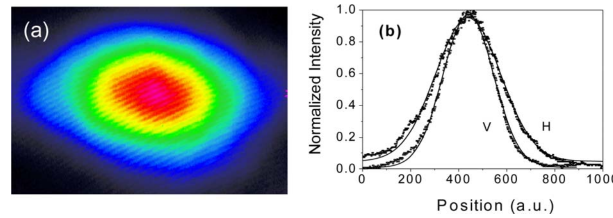

Fig. 6. (Color online) Energy distribution of the generated blue beam in the far field. (a) Color plot of beam energy. (b) Beam profile in the vertical (V) and horizontal (H) planes and the corresponding Gaussian fits.

Figure 6(b) shows the beam profile along the two orthogonal axes. The data appear to confirm a Gaussian distribution, although full confirmation of TEM_{00} character requires measurements of M^2 values. The ellipticity of the spot is 0.69, attributed to spatial walk-off as well as the astigmatism of the signal beam caused by the relatively large tilt angles (15°) on M_1 and M_2 to extract the blue beam out of the compact ring cavity.

In conclusion, we have demonstrated a new cw solid-state source for the 425–489 nm spectral range in the blue, providing nearly 450 mW of single-frequency output using intracavity doubling of a cw SRO based on MgO:sPPLT. The current tuning range is limited by the grating period of the MgO:sPPLT crystal and so can be extended to cover the entire range of 300–530 nm using alternative gratings. The use of other grating periods will also enable blue generation at lower temperatures, reducing the effects of thermal lensing, and thus extending the higher powers to shorter wavelengths. Moreover, by resonating the idler wave in the 1140–1420 nm range, tunable generation across the 570–710 nm will also be possible, making this a promising approach for the generation of high-power, widely tunable, cw radiation across the 300–700 nm spectral range.

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